Research Article

Experimental and Theoretical Research on the Stress-Relaxation Behaviors of PTFE Coated Fabrics under Different Temperatures

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As polymer composites, the stress-relaxation behaviors of membrane materials have significant effects on the pattern cutting design, the construction process analysis, and the stiffness degradation of membrane structures in the life cycle. In this paper, PTFE coated fabric is taken as the research object. First, the stress-relaxation behaviors under different temperatures (23°C, 40°C, 50°C, 60°C, and 70°C) are studied, and the variations of main mechanical parameters are got. Then, a simple review of several current viscoelastic models is presented. Finally, several common models for the material viscoelasticity are used to compare with the test results. Results show PTFE coated fabric is typically viscoelastic. The stress relaxation is obvious in the initial phase and it decreases with time increasing. The stress decreases significantly and then tends to a stable value. With temperature increasing, the decrease rate of membrane stress decreases and the final stable value increases. This material performs obvious hardening with temperature increasing. Most of the current models can make good prediction on the stress-relaxation behaviors of PTFE coated fabrics under different temperatures. The results can be references for the determination of pattern shrinkage ratio and construction process analysis of membrane structures.

1. Introduction

At the beginning of the 1970s, glass fibers coated with PTFE (polytetrafluoroethylene) developed by the NASA were first used in civil engineering. Among the commonly used membrane materials, the glass fibers coated with PTFE are welcomed by the designers for their good durability and stiffness [1]. Many famous landmark membrane structures are built with PTFE coated fabrics, for example, membrane roof of EXPO Axis in Shanghai, China (Figure 1), and Shenzhen Baoan Stadium in Guangdong, China (Figure 2). The PTFE coated fabric is obviously nonlinear, anisotropic, and viscoelastic plastic under tensile loading. Its mechanical properties are affected by the loading history, as well as the woven structure and coating type. Significant viscoelastic characteristics including creep and stress relaxation can be observed in the material tests [2–4]. Besides, as a typical polymer composite, the viscoelastic characteristics should be considered in the design and analysis of membrane structures [5, 6].

The overall stiffness of membrane structures is supported by the prestress and the curvature form of membrane surfaces. The process of pattern cutting and the joining of separate parts are carried out under the zero stress state. Then, the membrane materials are stretched to the initial state during the forming process and the prestress is the main loading. Therefore, the membrane materials should be transformed from the initial state to the zero stress state, which is also called “the cutting pattern design” [1]. Due to the nonlinear and viscoelastic properties of membrane materials, the shrinkage compensation should be considered in the pattern cutting design, as shown in Figure 3. Obviously, the shrinkage ratio is related with the membrane stress state and the improper value will affect the forming of membrane structures [7–11].

The determination of shrinkage ratio is a key and complex technology and there are few published references about this aspect. In actual engineering, the determination of shrinkage ratio is always got by experience or simple tests and it is always

FIGURE 1: Membrane roof of Shanghai EXPO Axis.

FIGURE 2: Shenzhen Baoan Stadium, China.

the secret technology of many companies. The European design guide for tensile surface structures proposed that the long-term strain curves of membrane material can be got through the biaxial cyclic tests by incorporating the effects of temperature and time [1]. The shrinkage ratio can be got according to the curves of long-term strain. The Japanese researchers also conducted the biaxial cyclic tests to get the shrinkage ratio, but the corresponding test protocols are different from that of the European recommendations [12]. Some researchers used the viscoelastic models to get the shrinkage ratio and the parameters in the viscoelastic models can be got by uniaxial creep tests [13]. Besides, after stretched forming, significant stress relaxation will appear in the membrane surface under the interaction of wind and snow, which may lead to the reduction and redistribution of membrane stress [14–16]. Therefore, the viscoelastic properties of membrane materials should be considered in the cutting pattern design and construction process analysis [11].

Nowadays, the viscoelastic constitutive models are built by adding the viscous components to the elastic constitutive models. Actually, plastic strains can be observed under a very low stress state and they perform significant memory characteristics subject to the loading history. There are two principal methods to get the constitutive relations, macroscopic models and microscopic models. The microscopic models are built by the properties of yarns, coatings, and interfaces [11, 17]. They can reflect the deformation mechanisms of internal structures, but there are always too many unknown parameters. They may decrease the application

efficiency and increase the computation complexity. Therefore, many researches choose the macroscopic mathematical models to describe the viscoelastic properties of coated fabrics. The mathematical models are always composed of elastic components and viscous components, such as Maxwell model, Kelvin model, and generalized viscoelastic model [18, 19]. Besides, some researchers conduct the three-component model, four-component model, multicomponent model, fractional Maxwell model, fractional exponential model, and others to describe the viscoelastic behavior of materials. The studies show that with the prediction accuracy increases with parameter number increasing, but too many unknown parameters are also not convenient to the engineering application. As shown in the existing references, the linear viscoelastic models are always used in the current analysis, and the prediction accuracy needs to be improved.

As polymer composites, the mechanical properties of coated fabrics should be sensitive to temperature and loading protocols [5, 6]. Recently, many scholars studied the effect of temperature on the mechanical properties of polymer materials. Minte carried out a series of tests on the materials and connections and proposed the corresponding temperatures influence factors [20]. Zhang et al. proposed the temperature influence coefficient of tensile strength for coated fabrics by experimental researches [21]. Wang et al. used the regression method to fit the test data under two different temperatures [22]. Ambroziak and Kosowski described the test method to study the effect of temperature on mechanical properties of PVC-coated polyester fabric used in tensile membrane structures and proposed two nonlinear models for constitutive relations, the piecewise linear model and the Murnaghan model [23]. From above, the current researches are mainly imposed on the variations of tensile strength and breaking strain under different temperatures. However, there are few references on the stress relaxation of PTFE coated fabrics under different temperatures. The effects of temperature on the material viscoelastic behaviors should be considered, which may be important for the cutting pattern analysis and construction process analysis of membrane structures.

First, this paper studied the stress relaxation of PTFE membrane materials under different temperatures by uniaxial tests. Then, a simple review of several current viscoelastic models is presented. Finally, several viscoelastic models are used to describe the variation law of relaxation modulus, and the fitting accuracies are compared.

2. Materials and Test Setup

In this study, the Sheerfill-II manufactured by the Saint Gobain Company is taken as the research object. The specimens are with the length of 300 mm and the width of 50 mm, and the gauge distance is 200 mm. The thickness is 0.8 mm. The tests are carried out by the electronic tensile machine with temperature test box, as shown in Figure 4. During the experiment, the specimens should be put in the temperature box at least 1 hour before the tests. The temperatures are 23°C, 40°C, 50°C, 60°C, and 70°C, respectively. The initial prestress is 4 kN/m and the test time of stress relaxation is 72 hours.

FIGURE 3: Shrinkage compensation from the initial state to the zero stress state.

FIGURE 4: Uniaxial tensile machine with temperature box.

3. Current Viscoelastic Constitutive Models

Several common viscoelastic constitutive models are introduced and the corresponding expressions for stress relaxation are listed.

3.1. Classic Maxwell Model. The classic Maxwell models are composed of one spring and one viscous component. At constant initial stress, total strain of elastic component and the viscous component is shown as follows:

$$\varepsilon = \varepsilon_1 + \varepsilon_2, \quad (1)$$

where $\sigma_1 = E\varepsilon_1$ is the expressions of the spring component and $\sigma_2 = \eta\dot{\varepsilon}_2$ is the expressions of the viscous component. The balance equation is $\sigma_1 = \sigma_2 = \sigma$ and the deformation coordination equation is $\varepsilon = \varepsilon_1 + \varepsilon_2$.

At a constant strain, the differential equation can be obtained; the stress-relaxation expression of classic Maxwell models is shown as follows:

$$\sigma(t) = E\varepsilon_0 e^{-t/\tau_i}, \quad (2)$$

where $\tau_i = \eta_i/E_i$ is the relaxation time of the Maxwell component, E is the elastic modulus, and ε_0 is the initial

strain. From (2), the decrease rate of stress relaxation is related with η/E and the relaxation time τ_i is related with material properties. With the viscous value η decreasing, the relaxation time decreases and the relaxation rate increases. If $\eta \rightarrow \infty$, the stress relaxation will end, which is the horizontal section of the stress-relaxation curves.

3.2. Generalized Viscoelastic Models (Three-Component Model, Five-Component Model, and Seven-Component Model). The Maxwell models are composed of spring and viscous components. The generalized Maxwell model is composed of several Maxwell models, as shown in Figures 5(a) and 5(b). The constitutive relation of Maxwell model is $\dot{\varepsilon}_1 = \dot{\sigma}_1/E + \sigma_1/\eta$ and the constitutive relation of the spring model is $\sigma_2 = E_2\varepsilon_2$.

Based on the balance equation and deformation coordinate equation, the constitutive relation of three-component model is as follows:

$$\dot{\varepsilon} = \dot{\varepsilon}_1 = \frac{\dot{\sigma}_1}{E_1} + \frac{\sigma_1}{\eta} = \frac{1}{E_1} (\dot{\sigma} - \dot{\sigma}_2) + \frac{1}{\eta} (\sigma - \sigma_2). \quad (3)$$

By introducing the unit jump function, the expression for relaxation modulus is shown as follows:

$$Y(t) = E_e + \sum_{i=1}^n E_i e^{-t/\tau_i}, \quad (4)$$

where the E_e is the final relaxation modulus and $\tau_i = \eta_i/E_i$ is the relaxation time of the i th Maxwell component. ε_0 is the initial strain.

3.3. Fractional Maxwell Model. The fractional Maxwell models are mathematically composed of the spring and viscous components. The classic Maxwell model is composed of spring and viscous components [24, 25]. If we replace the spring and viscous components by two fractional viscoelastic models, then a fractional Maxwell model is created, as shown in Figure 5(c).

The constitutive relations can be described as follows:

$$\sigma(t) + \frac{E_1\tau_1^\alpha}{E_2\tau_2^\beta} \frac{d^{\alpha-\beta}\sigma(t)}{dt^{\alpha-\beta}} = E_1\tau_1^\alpha \frac{d^\alpha\varepsilon(t)}{dt^\alpha}. \quad (5)$$

FIGURE 5: Several viscoelastic models.

The expressions of fractional Maxwell relaxation modulus can be got by the Fourier transform and Mellin inverse transform.

If $0 \leq \beta < \alpha < 1$, the relaxation modulus can be got as follows:

$$Y(t) \cong \frac{E}{\Gamma(1-\beta)} \left(\frac{t}{\tau}\right)^{-\beta} \quad (t \ll \tau)$$

$$Y(t) \cong \frac{E}{\Gamma(1-\alpha)} \left(\frac{t}{\tau}\right)^{-\alpha} \quad (t \gg \tau), \quad (6)$$

where α is the attenuation index, τ is the attenuation characteristic time, E is the modulus, and $\Gamma(x)$ is the complete Gamma function.

3.4. Fractional Exponential Model. Due to the similarity of constitutive relations of elastic and viscoelastic bodies, the answer of the correspondence principle in viscoelastic problems can be got, according to elastic problems. In order to achieve the relationship between the nonlinear viscoelastic constitutive relation and the nonlinear elastic constitutive relationship, the viscoelastic constitutive theory of the elasticity recovery correspondence principle is proposed by Zhang [26]. Then, the fractional exponential model is proposed, as shown in

$$Y(t) = Y_{\infty} + (Y_0 - Y_{\infty}) \exp \left\{ -\beta [(\gamma + \alpha)t]^{1-\alpha} \right\}, \quad (7)$$

where Y_{∞} is the long-term relaxation modulus, Y_0 is the transient relaxation modulus, and α , β , and γ are the parameters.

3.5. Burgers Model. The Burgers model is a combination model composed of a Maxwell model and a Kevin model. It is always called “four-component model,” due to the four components in its expression. The Burgers model is a common model that can describe the material viscoelastic behaviors.

The constitutive relation of Maxwell model is $\dot{\epsilon}_1 = \dot{\epsilon}'_1 + \dot{\epsilon}''_1 = \dot{\sigma}_1/E_1 + \sigma_1/\eta_1$ and the constitutive relation of Kevin model is $\sigma_2 = \sigma'_2 + \sigma''_2 = E_2\dot{\epsilon}_2 + \eta_2\dot{\epsilon}_2$. The expressions of

the balance and deformation coordination conditions are $\sigma = \sigma_1 = \sigma_2$ and $\epsilon = \epsilon_1 + \epsilon_2$.

Therefore, the differential expressions of Burgers model are got as follows:

$$E_2\dot{\epsilon} + \eta_2\ddot{\epsilon} = \frac{\eta_2}{E_1} \left[\ddot{\sigma} + \left(\frac{E_1}{\eta_1} + \frac{E_1}{\eta_2} + \frac{E_2}{\eta_2} \right) \dot{\sigma} + \frac{E_1E_2}{\eta_1\eta_2} \sigma \right]$$

$$\sigma(0^+) = E_1\epsilon(0^+) \quad (8)$$

$$\dot{\sigma}(0^+) = E_1\dot{\epsilon}(0^+) - E_1^2 \left(\frac{1}{\eta_1} + \frac{1}{\eta_2} \right) \epsilon(0^+).$$

The expressions of Burgers model for the material stress-relaxation behaviors are shown in

$$Y(t) = \frac{E_1}{\alpha - \beta} \left[\left(\frac{E_2}{\eta_2} - \beta \right) e^{-\beta t} - \left(\frac{E_2}{\eta_2} - \alpha \right) e^{-\alpha t} \right], \quad (9)$$

where $\alpha = (p_1 + \sqrt{p_1^2 - 4p_2})/2p_2$; $\beta = (p_1 - \sqrt{p_1^2 - 4p_2})/2p_2$; $p_1 = \eta_1/E_1 + (\eta_1 + \eta_2)/E_2$; and $p_2 = \eta_1\eta_2/E_1E_2$.

4. Results and Discussions

4.1. Experimental Results of Stress-Relaxation Tests. The stress-strain curves of PTFE coated fabrics under different temperatures are shown in Figure 6. The relaxation modulus can be got by dividing the stress by the strain and the relaxation curves under different temperatures are shown in Figure 7. The stress-time curves are nonlinear, and there is a linear relationship between the logarithm of relaxation modulus and time. In the first three hours, the stress relaxation has completed 80% of the total relaxation value. In the following, the stress gradually reaches a stable value. The changing of temperature has few effects on the curves of stress relaxation and relaxation modulus. With temperature increasing, the rate of stress relaxation is faster, and it is easy to reach the stable state. The stable value increases with temperature increasing, which is different from other traditional materials (e.g., PVC-coated fabrics). The material performs obvious hardening with temperature increasing, which is consistent with the material behaviors in cyclic loading tests [27, 28].

FIGURE 6: Stress-relaxation curves of PTFE coated fabrics under different temperatures.

FIGURE 7: Relaxation modulus of PTFE coated fabrics under different temperatures.

4.2. Comparisons of Experimental Results of Stress-Relaxation Tests. The above constitutive models are used to analyze the stress-relaxation behaviors of PTFE coated fabrics and the prediction accuracy of several models is compared.

4.2.1. Classic Maxwell Model. The classic Maxwell models are fitted by (2) and the fitting results are shown in Figure 8. The results show that the classic Maxwell models cannot be used to analyze the stress-relaxation behaviors of PTFE coated fabrics.

4.2.2. Generalized Maxwell Model (Three-Component Model, Five-Component Model, and Seven-Component Model). The generalized Maxwell models (three-component model, five-component model, and seven-component model) are used to fit the relaxation modulus of PTFE coated fabrics under different temperatures. All three models are got by self-defined formulas. The fitting results are compared with the test data and the corresponding prediction accuracy is compared, as shown in Figures 9, 10, and 11, respectively. The fitted parameters of three models are listed in Tables 1, 2, and 3, respectively.

FIGURE 8: Prediction results of the classic Maxwell model.

FIGURE 9: Predictions of the generalized Maxwell model (three-component model).

4.2.3. Fractional Maxwell Model. In order to express the stress-relaxation behaviors directly, the stress-relaxation behavior can be described as follows:

$$Y(t) \cong \frac{E}{\Gamma(1-\beta)} \left(\frac{t}{\tau}\right)^{-\beta}. \quad (10)$$

Here, if $k_1 = E\tau^\beta/\Gamma(1-\beta)$, the above function can be simplified as follows:

$$\lg Y(t) = \lg k_1 - \beta \lg t. \quad (11)$$

The fractional Maxwell models are fitted by (11) and the fitting results are shown in Figure 12 and Table 4.

FIGURE 10: Predictions of the generalized Maxwell model (five-component model).

FIGURE 11: Predictions of the generalized Maxwell model (seven-component model).

4.2.4. Fractional Exponential Model. The fractional exponential models are fitted by self-defined formulas and the fitting results are shown in Figure 13 and Table 5.

4.2.5. Burgers Model. The Burgers model is fitted by self-defined formulas and the fitting results are shown in Figure 14 and Table 5.

From the above, all the above viscoelastic models can describe the stress-relaxation behaviors of PTFE coated fabrics under different temperatures. However, the expressions of classic Maxwell models are relatively simple, compared with the other models. They have strict guidelines for the application of the ordinary differential equations in describing the complex constitutive relations. They can only describe the simple trend of stress relaxation and cannot

TABLE 1: Parameter results of the generalized Maxwell model (three-component model).

	Warp					Weft				
	23°C	40°C	50°C	60°C	70°C	23°C	40°C	50°C	60°C	70°C
E_e	56.83	53.54	57.94	57.33	58.92	59.75	54.33	53.63	57.78	61.11
E_1	14.43	11.69	11.09	12.51	9.83	13.94	11.50	12.41	11.16	10.83
E_2	13.21	9.69	11.87	11.90	12.37	13.83	13.20	9.73	10.12	8.72
E_3	16.74	12.32	11.39	10.74	11.03	18.31	14.02	11.44	13.31	12.33
$1/\tau_1$	0.05	$5.63E-2$	$7.43E-2$	$4.37E-5$	$3.13E-5$	$3.62E-5$	$3.43E-5$	$2.19E-3$	0.081	$7.78E-2$
$1/\tau_2$	$3.78E-5$	$4.16E-5$	$1.98E-3$	$2.37E-3$	$2.29E-3$	$1.27E-3$	$5.53E-2$	$4.48E-5$	$5.42E-5$	$1.04E-4$
$1/\tau_3$	$1.75E-3$	$2.05E-3$	$4.03E-5$	0.087	0.082	0.041	$1.86E-3$	0.059	$3.76E-3$	$3.68E-3$

TABLE 2: Parameter results of the generalized Maxwell model (five-component model).

	Warp					Weft				
	23°C	40°C	50°C	60°C	70°C	23°C	40°C	50°C	60°C	70°C
E_e	54.66	52.81	56.56	56.92	58.66	59.28	52.49	52.63	52.59	60.86
E_1	3.13	2.49	2.60	2.33	2.17	2.87	3.26	2.61	2.74	2.07
E_2	11.52	6.29	7.94	7.43	7.59	14.27	9.02	8.92	8.59	8.00
E_3	8.74	7.25	7.27	10.55	7.11	8.94	10.04	5.91	8.11	8.13
E_4	8.71	7.96	8.14	6.68	6.58	7.07	7.59	6.76	11.82	6.27
E_5	12.21	8.64	8.20	7.31	8.92	11.70	8.14	8.44	9.06	6.24
$1/\tau_1$	0.21	0.22	0.34	0.43	0.44	0.24	0.18	0.21	0.41	0.31
$1/\tau_2$	0.019	$2.96E-4$	0.002	0.0045	0.047	0.024	0.0019	0.022	$2.82E-8$	0.040
$1/\tau_3$	$1.31E-4$	$1.96E-5$	$2.02E-4$	$2.99E-5$	0.0049	$3.64E-4$	0.018	$2.09E-4$	$6.20E-5$	0.0055
$1/\tau_4$	$1.0E-5$	0.0028	$1.45E-5$	$4.87E-4$	$7.36E-4$	0.0026	$1.57E-4$	$1.70E-5$	0.023	$7.11E-4$
$1/\tau_5$	0.0017	0.024	0.029	0.043	$2.42E-5$	$2.50E-5$	$9.86E-6$	0.0022	0.0019	$5.79E-5$

give a more accurate description. This aspect can also be seen in the application of Burgers model. The Burgers model can reflect the stress-relaxation behaviors of PTFE coated fabrics, because it is composed of the Maxwell model and the Kevin model. To a certain extent, it should reflect both the stress-relaxation behavior and the creep behavior. However, as we know, the Kevin model can only reflect the material creep behaviors and the Maxwell model can only reflect the material stress-relaxation behaviors. When predicting the stress-relaxation behaviors, the Burgers model can be degenerated into the classic Maxwell model. Therefore, it cannot make good prediction for the material stress-relaxation behaviors. For the generalized Maxwell models, the equations are composed of classic Maxwell models and spring components. More parameters make it easy to describe the stress-relaxation behaviors accurately. Besides, the final modulus is given, which is the stable modulus when the time is the infinity. Therefore, it can reflect the “memory” characteristics of coated fabrics and can predict the stress-relaxation behaviors. The fractional Maxwell models and the fractional exponential models can solve the prediction limitation of ordinary differential equations. They can achieve the interpolation calculation between elastic behaviors and viscous behaviors. Therefore, the fractional Maxwell models and the fractional exponential models are more suitable for describing the stress-relaxation behaviors of PTFE coated fabrics.

5. Conclusions

(1) The PTFE coated fabrics are typically viscoelastic. The stress decreases obviously in the initial state and it has completed 80% of the total relaxation in the first three hours. The decrease rate decreases with time increasing, and finally the stress gradually reaches a stable value. The stress-time curves are nonlinear, and there is a linear relationship between the logarithm of relaxation modulus and time. There are no significant differences between the behaviors of warp and weft.

(2) The changing of temperature has few effects on the curves of stress relaxation and relaxation modulus. With temperature increasing, the rate of stress relaxation is faster, and it is easy to reach the stable value. With temperature increasing, the relaxation modulus increases and the final stable value increases. This is consistent with the behaviors under cyclic loading in previous references, which may be related with the properties of glass fibers.

(3) The classic Maxwell model cannot make good prediction for the material stress-relaxation behaviors, due to fewer parameters. From the expressions, it can be seen that the Burgers model can reflect the stress-relaxation behaviors of PTFE coated fabrics, because the Burgers model is composed of the Maxwell model and the Kevin model. However, when using the Burgers model to predict the stress-relaxation behaviors, its expression is very close to the classic Maxwell

TABLE 3: Parameter results of the generalized Maxwell model (seven-component model).

	Warp					Weft				
	23°C	40°C	50°C	60°C	70°C	23°C	40°C	50°C	60°C	70°C
E_e	53.63	53.80	55.47	52.19	35.41	33.56	33.13	51.13	33.71	33.27
E_1	1.77	2.11	1.46	2.24	2.19	2.87	2.05	1.41	2.74	1.95
E_2	6.80	7.60	5.35	7.16	11.24	8.82	5.58	6.10	8.07	6.41
E_3	4.94	3.57	6.77	5.78	7.63	14.24	6.49	5.64	8.39	5.86
E_4	9.51	6.46	5.97	7.10	11.48	6.91	6.98	6.56	8.56	7.81
E_5	8.45	7.62	5.51	6.48	6.49	11.13	21.84	5.23	8.53	0.72
E_6	7.17	6.73	5.26	8.42	7.21	13.01	7.21	5.02	9.06	7.68
E_7	8.23	$9.59E-8$	6.31	3.95	9.36	13.58	8.60	5.49	11.82	8.00
$1/\tau_1$	0.37	0.26	0.69	0.45	0.44	0.24	0.29	0.37	0.41	0.33
$1/\tau_2$	0.060	0.0048	0.10	0.0053	$-1.1E-7$	$3.88E-4$	$1.36E-5$	0.0025	$6.24E-5$	$8.83E-4$
$1/\tau_3$	$3.98E-4$	$4.19E-7$	$7.61E-6$	$-1.6E-7$	0.046	0.024	$1.28E-4$	0.066	$4.21E-7$	$7.68E-5$
$1/\tau_4$	0.0019	$4.59E-5$	0.0025	0.048	$-1.1E-7$	0.0027	0.0011	0.013	$4.12E-7$	$6.68E-8$
$1/\tau_5$	0.012	0.034	$6.37E-5$	$6.33E-4$	$7.01E-4$	$2.86E-5$	$3.92E-7$	$5.83E-6$	$4.07E-7$	$2.47E-5$
$1/\tau_6$	$7.11E-5$	$6.02E-4$	$4.07E-4$	$2.01E-5$	0.0048	$1.70E-7$	0.047	$4.83E-4$	0.0019	0.044
$1/\tau_7$	$6.49E-6$	-5.93	0.016	$7.17E-5$	$2.22E-5$	$1.72E-7$	0.0073	$5.61E-5$	0.023	0.0065

FIGURE 12: Prediction of the fractional Maxwell model.

TABLE 4: Parameter results of the fractional Maxwell model.

Temperature	Warp		Weft	
	k_1	β	k_1	β
23°C	4.0214	0.04896	3.9919	0.04798
40°C	3.9836	0.04176	3.9996	0.04512
50°C	3.9389	0.03832	3.9811	0.04183
60°C	3.9452	0.03903	3.9033	0.03990
70°C	3.9006	0.03639	3.9312	0.03751

model. Therefore, it cannot make good prediction of stress-relaxation behaviors of PTFE coated fabrics under different temperatures.

(4) For the generalized Maxwell models, all three models including three-component model, five-component model, and seven-component model can make good predictions for the material stress-relaxation behaviors. Among them, the prediction accuracy of the seven-component model is the best, which indicates that, with equation parameter increasing, the prediction accuracy of fitting results increases.

TABLE 5: Parameter results of the Burgers model.

	Warp					Weft				
	α	β	η_2	E_1	E_2	α	β	η_2	E_1	E_2
23°C	0.0048	$1.21E-6$	17.24	93.33	0.058	0.0074	$1.42E-6$	13.89	80.63	0.072
40°C	0.0062	$9.60E-7$	14.71	80.26	0.067	0.0059	$1.05E-6$	15.38	84.41	0.064
50°C	0.0054	$1.11E-6$	15.63	88.41	0.064	$1.08E-6$	0.0062	14.93	84.97	0.067
60°C	$1.11E-6$	0.0052	15.87	89.36	0.062	$8.63E-7$	0.0081	-12.99	89.88	-0.077
70°C	0.0066	$8.86E-7$	14.24	80.31	0.071	$6.46E-7$	0.0071	13.70	90.48	0.072

(a) Warp

(b) Weft

FIGURE 13: Prediction of the fractional exponential model.

(a) Warp

(b) Weft

FIGURE 14: Prediction of the Burgers model.

(5) The fractional Maxwell model and the fractional exponential model are all built by self-defined formulas, and the fitting results are good. They can make good prediction of the final relaxation modulus and make worse prediction of the initial phase of the stress relaxation. Further research should be imposed on proposing a more accurate model to describe the whole phase of the stress relaxation.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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